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SEARCH FOR RARE AND FORBIDDEN CHARM MESON DECAYS AT FERMILAB E791

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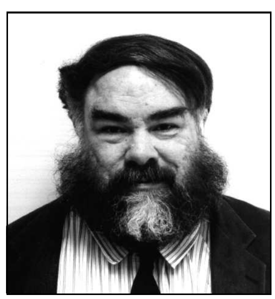

We report the results of a *blind* search for flavor-changing neutral current, lepton-flavor violating, and lepton-number violating decays of D^+, D_s^+, and D^0 mesons (and their antiparticles) into modes containing muons and electrons. Using data from Fermilab charm hadroproduction experiment E791, we examine the $\pi\ell\ell$ and $K\ell\ell$ decay modes of D^+ and D_s^+ and the $\ell^+\ell^-$ decay modes of D^0. No evidence for any of these decays is found. Therefore, we present branching-fraction upper limits at 90% confidence level for the 24 decay modes examined. Eight of these modes have no previously reported limits, and fourteen are reported with significant improvements over previously published results.

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RECHERCHE DE DÉSINTÉGRATIONS DE MÉSONS CHARMÉS PAR MODES RARES ET/OU INTERDITS PAR L'EXPÉRIENCE E791 À FERMILAB

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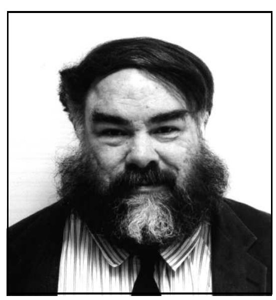

Les résultats d'une recherche *aveugle* portant sur des courants neutres de changement de saveur ou des violations de la conservation de la saveur ou du nombre leptonique sont présentées à partir de l'étude de désintégrations des mésons charmés D^+, D_s^+, et D^0 ainsi que leur antiparticules via des modes contenant soit des électrons, soit des muons. Basé sur l'échantillon de données amassées par l'expérience d'hadroproduction de charme E791 à Fermilab, nous examinons les modes de désintégration de D^+ et D_s^+ via $\pi\ell\ell$ et $K\ell\ell$ ainsi que $D^0 \to \ell^+\ell^-$. Aucune évidence pour ces types de désintégration n'a été trouvée. Nous dérivons donc des limites supérieures correspondant à des intervalles de confiance de 90% pour les 24 modes examinés. Huit de ces limites n'avaient jamais été mesurées au préalable et quatorze autres représentent une amélioration considérable sur les limites antérieures.

One way to discover physics beyond the Standard Model is to search for decays that are forbidden or else are predicted to occur at a negligible level. If seen, such decays might require new physics such as the introduction of a new particle to mediate the decays. Many experiments have examined decays of the charge 1/3 strange and beauty quarks.[1] Here, we look for rare and forbidden decays involving the charge 2/3 charm quark. Charge 2/3 quarks may couple differently than charge 1/3 quarks.[2]

We present the results of a search[3] for 24 decay modes of charmed D mesons and their antiparticles. These decay modes fall into three categories:

1. FCNC – flavor-changing neutral current decays ($D^0 \to \ell^+\ell^-$ and $D^+_{(d,s)} \to h^+\ell^+\ell^-$);

2. LFV – lepton-flavor violating decays ($D^0 \to \mu^\pm e^\mp$, $D^+_{(d,s)} \to h^+\mu^\pm e^\mp$, and $D^+_{(d,s)} \to h^-\mu^+e^+$, in which the leptons belong to different generations and h is π or K);

3. LNV – lepton-number violating decays ($D^+_{(d,s)} \to h^-\ell^+\ell^+$, in which the leptons belong to the same generation but have the same sign charge).

Decay modes belonging to (1) occur within the Standard Model via higher-order diagrams, but the branching fractions are at the 10^{-6} to 10^{-8} level,[4] below current sensitivity. However, if additional particles such as squarks or charginos exist, they could contribute additional amplitudes that would make these modes observable. Decays in (2) or (3) do not conserve lepton number and thus are forbidden. However, lepton number conservation is not required by Lorentz or gauge invariance, and a number of theoretical extensions to the Standard Model predict lepton-number violation.[2] The limits we present here for rare and forbidden dilepton decays of the D mesons are typically more stringent than those obtained from previous searches,[5,6,7,8,9] or else are the first reported.

The data are from Fermilab E791,[10] which recorded 2×10^{10} events at up to 10 MBytes/s.[11] These events were produced by a 500 GeV/c π^- beam in five target foils. Track and vertex reconstruction were provided by 23 silicon microstrip planes[12] and 45 wire chamber planes, plus two magnets.

Electron identification (ID) was based on transverse shower shape plus the match of tracks to shower positions and energies in our electromagnetic calorimeter.[13] ID efficiency varied from 62% below 9 GeV to 45% above 20 GeV. The probability to mis-ID a pion as an electron was about 0.8%.

Muon ID was obtained from two planes of scintillation counters. The first plane (5.5m $\times$ 3.0m) of 14 counters measured the horizontal x axis while the second plane (3.0m $\times$ 2.2m) of 16 counters measured the vertical y axis. The counters had 15 interaction lengths of shielding. Candidate muon tracks were required to pass cuts that were set using $D^+ \to \overline{K}^{*0}\mu^+\nu_\mu$ decays from our data.[14] Timing from the y counters was used to improve the x position resolution. Counter efficiencies were measured using muons originating from the primary beam dump, and were found to be $(99 \pm 1)\%$ for the y counters and $(69 \pm 3)\%$ for the x counters. The probability for misidentifying a pion as a muon decreased with momentum; from about 6% at 8 GeV/c to $(1.3 \pm 0.1)\%$ above 20 GeV/c.

After reconstruction of our 50 Terabyte data set,[15] events with evidence of well-separated production (primary) and decay (secondary) vertices were selected to separate charm candidates from background. Secondary and primary vertices had to be separated by more than $20\,\sigma_L$ for D^+ decays and more than $12\,\sigma_L$ for D^0 and D_s^+ decays, where σ_L is the calculated longitudinal resolution. The secondary vertex had to be separated from the closest material in the target foils by more than $5\,\sigma'_L$, where σ'_L is the separation uncertainty. The sum of the vector momenta of the tracks from the secondary vertex was required to pass within 40 μm of the primary vertex. Finally, the net momentum of the charm candidate transverse to the line connecting the production and decay vertices had to be less than 300, 250, and 200 MeV/c for D^0, D_s^+, and D^+ candidates, respectively. These cuts and our Čerenkov[16] kaon ID cuts were the same for each search mode and for its normalization mode.

We used a *blind* analysis technique. Before cuts were finalized, all events within a mass window ΔM_S around the mass of the D^+, D_s^+, or D^0 were *masked* so that the presence or absence of any potential signal would not bias our choice of cuts. All cuts were chosen by studying signal events generated by a Monte Carlo simulation program (see below) and background events from real data. Events within the signal windows were unmasked only after this optimization. Background events were chosen from a mass window ΔM_B above and below the signal window ΔM_S. The cuts were

chosen to maximize the ratio $N_S/\sqrt{N_B}$, where N_S and N_B are the numbers of signal and background events, respectively. We used asymmetric windows for the decay modes containing electrons to allow for the bremsstrahlung low-energy tail. The signal windows are:

$1.84 < M(D^+) < 1.90$ for $D^+ \to h\mu\mu$ $\quad 1.78 < M(D^+) < 1.90$ GeV/c^2 for $D^+ \to hee$ and $h\mu e$
$1.95 < M(D_s^+) < 1.99$ for $D_s^+ \to h\mu\mu$ $\quad 1.91 < M(D_s^+) < 1.99$ GeV/c^2 for $D_s^+ \to hee$ and $h\mu e$
$1.83 < M(D^0) < 1.90$ for $D^0 \to \mu\mu$ $\quad 1.76 < M(D^0) < 1.90$ GeV/c^2 for $D^0 \to ee$ and μe

We normalize the sensitivity of our search to topologically similar Cabibbo-favored decays. For the D^+ decays we use $D^+ \to K^-\pi^+\pi^+$; for D_s^+ we use $D_s^+ \to \phi\pi^+$; and for D^0 we use $D^0 \to K^-\pi^+$. The mass widths of our normalization modes were 10.5 MeV/c^2 for D^+, 9.5 MeV/c^2 for D_s^+, and 12 MeV/c^2 for D^0. The events within the $\sim 5\,\sigma$ window are shown in Figs. 1a–c. The upper limit for each branching fraction is $B_X = (N_X/N_{\rm Norm}) \cdot (\varepsilon_{\rm Norm}/\varepsilon_X) \cdot B_{\rm Norm}$, where N_X is the 90% CL upper limit on the number of decays for the rare or forbidden decay mode X, and ε_X is that mode's detection efficiency. $N_{\rm Norm}$ is the fitted number of normalization mode decays; $\varepsilon_{\rm Norm}$ is the normalization mode detection efficiency; and $B_{\rm Norm}$ is the normalization mode branching fraction.[17]

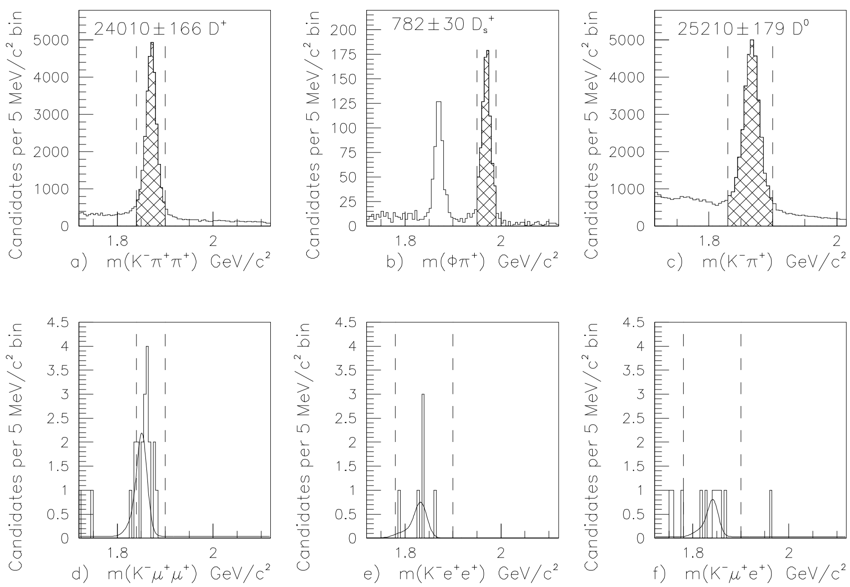

Figure 1: Top row: typical normalization charm signals. The signal region is shaded. Bottom row: invariant mass plots of D^+ candidate decays to $K^-\mu^+\mu^+$, $K^-e^+e^+$, and $K^-\mu^+e^+$, showing reflections mostly from misidentified $D^+ \to K^-\pi^+\pi^+$ decays. These modes are used to set mis-ID rate rather than upper limits The solid curves are normalized Monte Carlo fits. The dashed lines show the signal window.

The ratio of detection efficiencies is given by $\varepsilon_{\rm Norm}/\varepsilon_X = N^{\rm MC}_{\rm Norm}/N^{\rm MC}_X$, where $N^{\rm MC}_{\rm Norm}$ and $N^{\rm MC}_X$ are the fractions of Monte Carlo events that are reconstructed and pass final cuts, for the normalization and decay modes, respectively. We use Pythia/Jetset[18] as the physics generator and model the effects of resolution, geometry, magnetic fields, multiple scattering, interactions in the detector material, detector efficiencies, and the analysis cuts. The efficiencies for the normalization modes varied from about 0.5% to 2% and for the search modes varied from about 0.1% to 2%.

Monte Carlo studies show that the experiment's acceptances are nearly uniform across the Dalitz plots, except that the dilepton ID efficiencies typically drop to near zero at the dilepton mass threshold. The efficiency typically reaches its full value at masses only a few hundred MeV/c^2 above the dilepton mass threshold. We use a constant weak-decay matrix element when calculating the overall detection efficiencies. Two exceptions to the use of the Monte Carlo simulations in determining relative efficiencies are made: those for Čerenkov ID when the number of kaons in the signal and normalization modes are different, and those for the muon ID. These efficiencies are determined from data.

The 90% CL upper limits N_X are calculated using the method of Feldman and Cousins[19] to account for background, and then corrected for systematic errors by the method of Cousins and Highland.[20] In these methods, the numbers of signal events are determined by simple counting, not by a fit. All

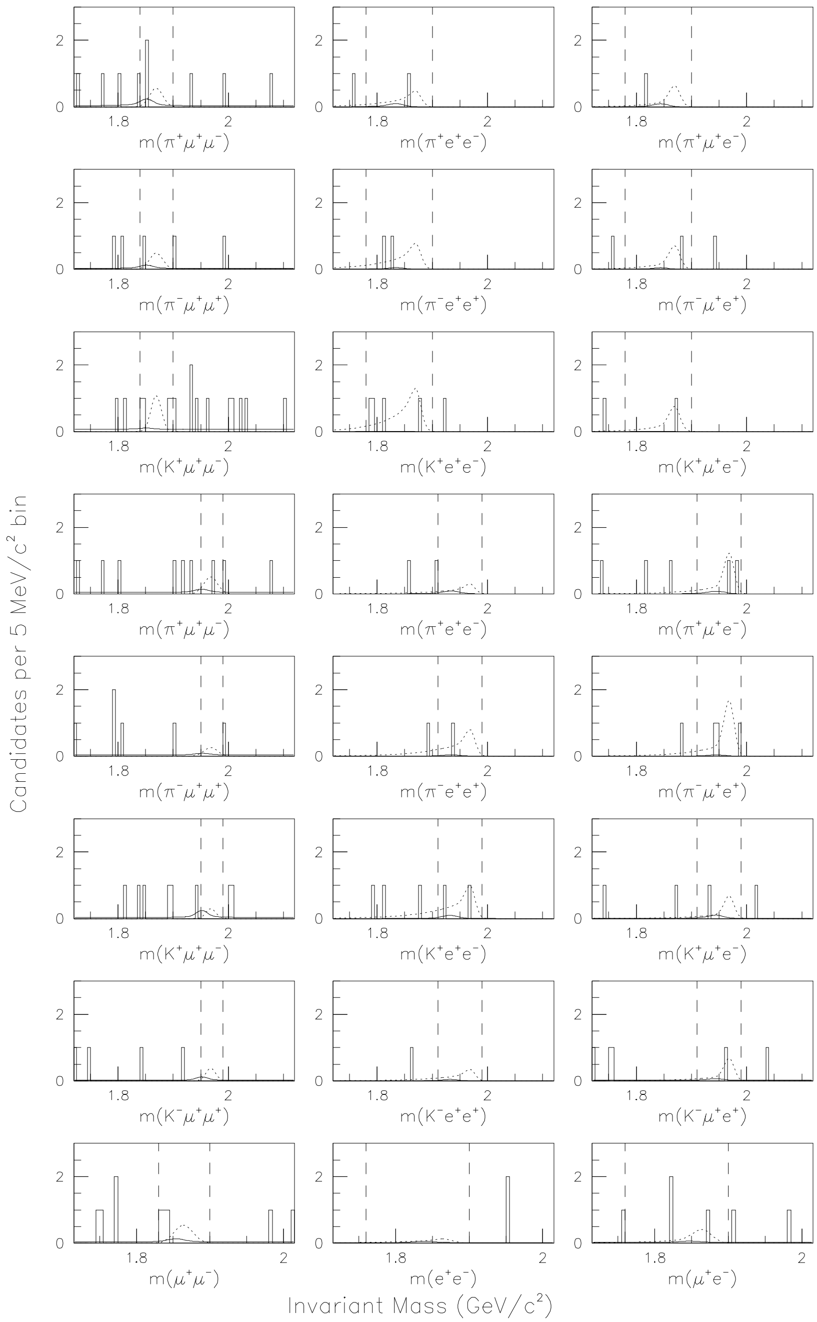

Figure 2: Final event samples for the D^+ (rows 1–3), D_s^+ (rows 4–7), and D^0 (row 8) decays. The solid curves represent estimated background; the dotted curves represent signal shape for a number of events equal to the 90% CL upper limit. The dashed vertical lines are ΔM_S boundaries.

results are listed in Table 1 and shown in Fig. 2. The kinematic criteria and removal of reflections (see below) are different for the D^+, D_s^+, and D^0. Thus, the D^+ and D_s^+ rows in Fig. 2 with the same decay particles are different, and the seventh row of Fig. 2 is different from the bottom row of Fig. 1.

The upper limits are determined by both the number of candidate events and the expected number of background events within the signal region. Background that is not removed by cuts include decays in which hadrons (from real, fully-hadronic decay vertices) are misidentified as leptons. In the case where kaons are misidentified as leptons, candidates have effective masses which lie outside the signal windows. Most of these originate from Cabibbo-favored modes $D^+ \to K^-\pi^+\pi^+$, $D_s^+ \to K^-K^+\pi^+$, and $D^0 \to K^-\pi^+$. These Cabibbo-favored reflections were explicitly removed prior to cut optimization. There remain two sources of background in our data: hadronic decays with pions misidentified as leptons ($N_{\rm MisID}$) and "combinatoric" background ($N_{\rm Cmb}$) arising primarily from false vertices and partially reconstructed charm decays. After cuts were applied and the signal windows opened, the

number of events within the window is $N_{\rm Obs} = N_{\rm Sig} + N_{\rm MisID} + N_{\rm Cmb}$.

The background $N_{\rm MisID}$ arises mainly from singly-Cabibbo-suppressed (SCS) modes. These misidentified leptons can come from hadronic shower punchthrough, decays-in-flight, and random overlaps of tracks. We do not attempt to establish a limit for $D^+ \to K^-\ell^+\ell^+$ modes, as they have relatively large feedthrough signals from copious Cabibbo-favored $K^-\pi^+\pi^+$ decays. Instead, we use the observed signals in $K^-\ell^+\ell^+$ channels to measure three dilepton mis-ID rates under the assumption that the observed signals (shown in Figs. 1d–f) arise entirely from lepton mis-ID. The curve shapes are from Monte Carlo. The following mis-ID rates were obtained: $r_{\mu\mu} = (7.3 \pm 2.0) \times 10^{-4}$, $r_{\mu e} = (2.9 \pm 1.3) \times 10^{-4}$, and $r_{ee} = (3.4 \pm 1.4) \times 10^{-4}$. Using these rates we estimate the numbers of misidentified candidates, $N^{h\ell\ell}_{\rm MisID}$ (for D^+ and D^+_s) and $N^{\ell\ell}_{\rm MisID}$ (for D^0), in the signal windows as follows: $N^{h\ell\ell}_{\rm MisID} = r_{\ell\ell} \cdot N^{h\pi\pi}_{\rm SCS}$ and $N^{\ell\ell}_{\rm MisID} = r_{\ell\ell} \cdot N^{\pi\pi}_{\rm SCS}$, where $N^{h\pi\pi}_{\rm SCS}$ and $N^{\pi\pi}_{\rm SCS}$ are the numbers of SCS hadronic decay candidates within the signal windows. For modes in which two possible pion combinations can contribute, e.g., $D^+ \to h^+\mu^\pm\mu^\mp$, we double the rate.

To estimate the combinatoric background $N_{\rm Cmb}$ within a signal window ΔM_S, we count events having masses within an adjacent background mass window ΔM_B, and scale this number ($N_{\Delta M_B}$) by the relative sizes of these windows: $N_{\rm Cmb} = (\Delta M_S/\Delta M_B) \cdot N_{\Delta M_B}$. To be conservative in calculating our 90% confidence level upper limits, we take combinatoric backgrounds to be zero when no events are located above the mass windows. In Table 1 we present the numbers of combinatoric background, mis-ID background, and observed events for all 24 modes.

Systematic errors in this analysis include: statistical errors from the fit to the normalization sample $N_{\rm Norm}$; statistical errors on the numbers of Monte Carlo events for both $N^{\rm MC}_{\rm Norm}$ and $N^{\rm MC}_X$; uncertainties in the calculation of mis-ID background; and uncertainties in the relative efficiency

Table 1: E791 90% confidence level (CL) branching fractions (BF) compared to previous experiments. The background and candidate events correspond to the signal region only.

Mode	(Est. $N_{\rm Cmb}$	BG) $N_{\rm MisID}$	Cand. Obs.	Syst. Err.	90% CL Num.	E791 BF Limit	Previous BF Limit	Previous Experiment
$D^+ \to \pi^+\mu^+\mu^-$	1.20	1.47	2	10%	3.35	1.5×10^{-5}	1.8×10^{-5}	E791 [5]
$D^+ \to \pi^+e^+e^-$	0.00	0.90	1	12%	3.53	5.2×10^{-5}	6.6×10^{-5}	E791 [5]
$D^+ \to \pi^+\mu^\pm e^\mp$	0.00	0.78	1	11%	3.64	3.4×10^{-5}	1.2×10^{-4}	E687 [6]
$D^+ \to \pi^-\mu^+\mu^+$	0.80	0.73	1	9%	2.92	1.7×10^{-5}	8.7×10^{-5}	E687 [6]
$D^+ \to \pi^-e^+e^+$	0.00	0.45	2	12%	5.60	9.6×10^{-5}	1.1×10^{-4}	E687 [6]
$D^+ \to \pi^-\mu^+e^+$	0.00	0.39	1	11%	4.05	5.0×10^{-5}	1.1×10^{-4}	E687 [6]
$D^+ \to K^+\mu^+\mu^-$	2.20	0.20	3	8%	5.07	4.4×10^{-5}	9.7×10^{-5}	E687 [6]
$D^+ \to K^+e^+e^-$	0.00	0.09	4	11%	8.72	2.0×10^{-4}	2.0×10^{-4}	E687 [6]
$D^+ \to K^+\mu^\pm e^\mp$	0.00	0.08	1	9%	4.34	6.8×10^{-5}	1.3×10^{-4}	E687 [6]
$D^+_s \to K^+\mu^+\mu^-$	0.67	1.33	0	27%	1.32	1.4×10^{-4}	5.9×10^{-4}	E653 [7]
$D^+_s \to K^+e^+e^-$	0.00	0.85	2	29%	5.77	1.6×10^{-3}		
$D^+_s \to K^+\mu^\pm e^\mp$	0.40	0.70	1	27%	3.57	6.3×10^{-4}		
$D^+_s \to K^-\mu^+\mu^+$	0.40	0.64	0	26%	1.68	1.8×10^{-4}	5.9×10^{-4}	E653 [7]
$D^+_s \to K^-e^+e^+$	0.00	0.39	0	28%	2.22	6.3×10^{-4}		
$D^+_s \to K^-\mu^+e^+$	0.80	0.35	1	27%	3.53	6.8×10^{-4}		
$D^+_s \to \pi^+\mu^+\mu^-$	0.93	0.72	1	27%	3.02	1.4×10^{-4}	4.3×10^{-4}	E653 [7]
$D^+_s \to \pi^+e^+e^-$	0.00	0.83	0	29%	1.85	2.7×10^{-4}		
$D^+_s \to \pi^+\mu^\pm e^\mp$	0.00	0.72	2	30%	6.01	6.1×10^{-4}		
$D^+_s \to \pi^-\mu^+\mu^+$	0.80	0.36	0	27%	1.60	8.2×10^{-5}	4.3×10^{-4}	E653 [7]
$D^+_s \to \pi^-e^+e^+$	0.00	0.42	1	29%	4.44	6.9×10^{-4}		
$D^+_s \to \pi^-\mu^+e^+$	0.00	0.36	3	28%	8.21	7.3×10^{-4}		
$D^0 \to \mu^+\mu^-$	1.83	0.63	2	6%	3.51	5.2×10^{-6}	4.1×10^{-6}	BEATRICE [8]
$D^0 \to e^+e^-$	1.75	0.29	0	9%	1.26	6.2×10^{-6}	8.2×10^{-6}	E789 [9]
$D^0 \to \mu^\pm e^\mp$	2.63	0.25	2	7%	3.09	8.1×10^{-6}	1.7×10^{-5}	E789 [9]

for each mode, including lepton and kaon tagging. These tagging efficiency uncertainties include: 1) the muon counter efficiencies from both Monte Carlo simulation and hardware performance; 2) kaon Čerenkov ID efficiency due to differences in kinematics and modeling between data and Monte Carlo simulated events; and 3) the fraction of signal events (based on simulations) that would remain outside the signal window due to bremsstrahlung tails. The larger systematic errors for the D_s^+ modes, compared to the D^+ and D^0 modes, are due to the uncertainty in the branching fraction for the D_s^+ normalization mode. The sums, taken in quadrature, of these systematic errors are listed in Table 1.

In summary, we use a *blind* analysis of data from Fermilab E791 to obtain upper limits on the dilepton branching fractions for flavor-changing neutral current, lepton-number violating, and lepton-family violating decays of D^+, D_s^+, and D^0 mesons. No evidence for any of these decays is found. The 90% confidence level branching fraction limits shown in Table 1 represent significant improvements over previously published results. In the future we hope to report results for 4-prong decays of the D^0 charm meson to a pair of leptons and either a neutral vector meson [21] or a $\pi\pi$, πK, or KK pair.

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